EME

From the Earth to the Moon (and back)

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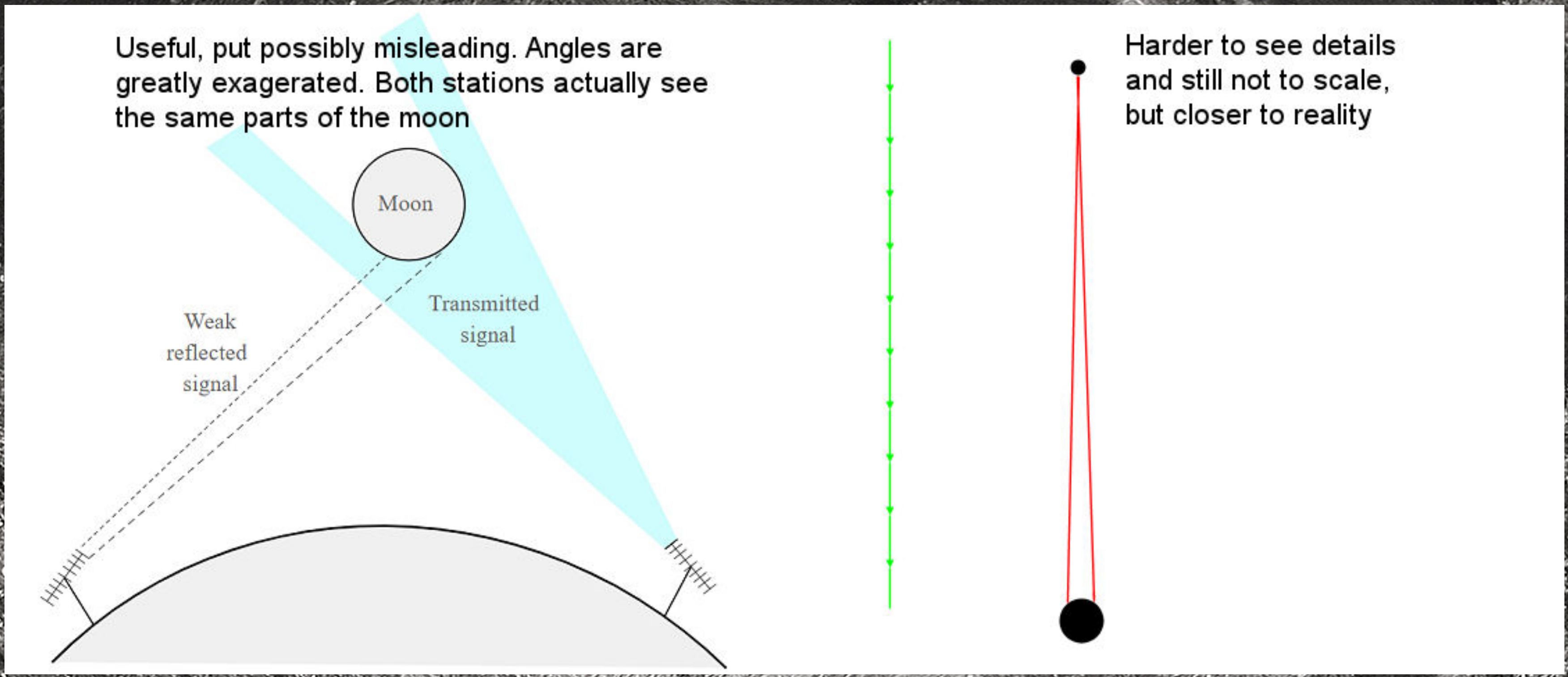
See http://www.bobatkins.com/radio/EME101.html

You are here

Brightness, size and distance pretty much to scale

It’s a long way to the Moon

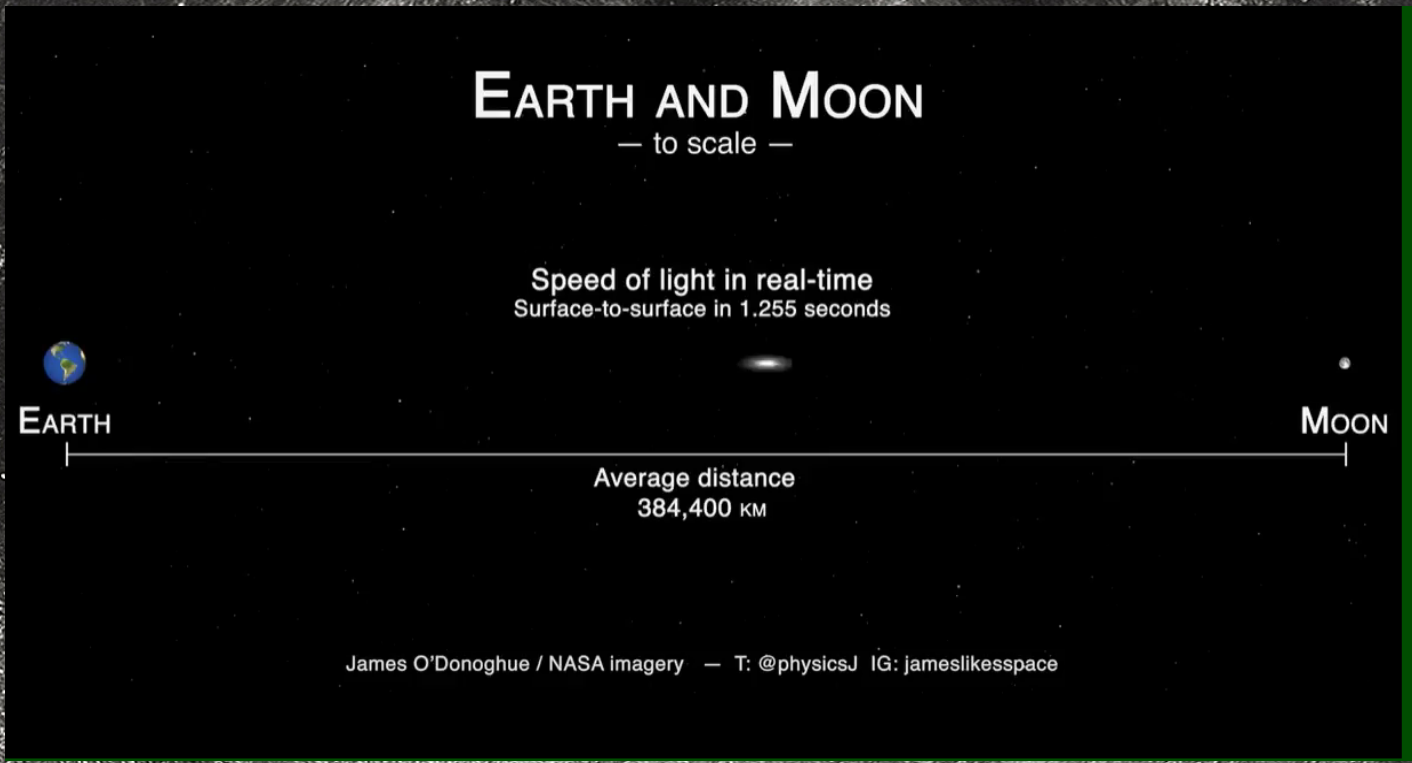
Typical diagrams greatly distort reflection angle at the moon’s surface



Time and Distance to scale

The reflection comes almost straight back. Typically the angle between the incident beam and reflected beam is of the order of 1 degree

Apollo 11 took 3 days to the moon. RF takes ~ 1.25 seconds



Leaving the Earth

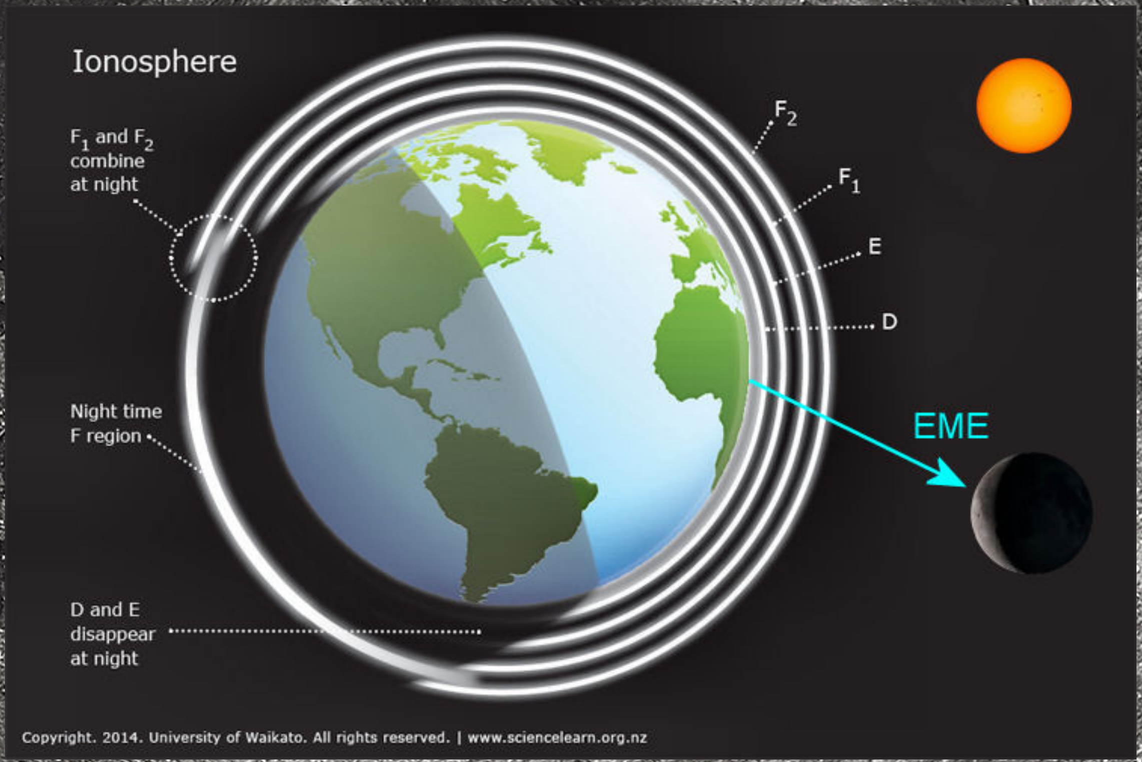
- First the signal passes through the Troposphere, the region in which weather occurs
- Below 10Ghz weather has little effect on EME signals
- At 24 GHz and up, there is absorption by gasses such as oxygen and water vapor so loss in minimized when humidity is low and the moon elevation is high
- At low elevation there can be some refraction which results in the RF signal “bending” downwards. This can effect optimum antenna aiming (especially on higher microwave bands)

The Ionosphere

- At heights from around 30 to 600 miles, residual atmospheric gases can be ionized by solar and cosmic radiation, leading to the formation of free electrons – a plasma.
- This creates a series of zones which can reflect HF signals. VHF and shorter wavelength signals are generally not reflected and so pass through the ionosphere with little attenuation
- However even VHF and higher frequency signals do not pass through the ionosphere without changes. There are polarization changes. especially below 23cm.

Ionosphere

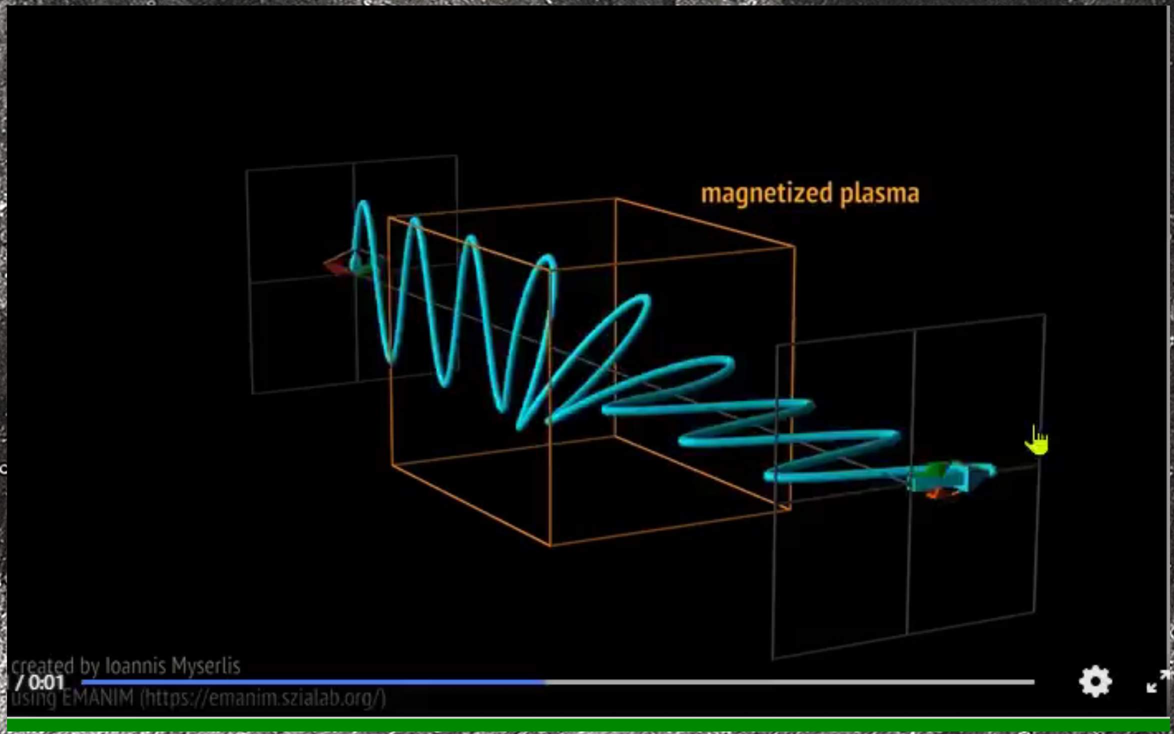
The ionosphere is not static. It changes between night and day, and is influenced by solar activity. Its effect on signals passing through it is not constant

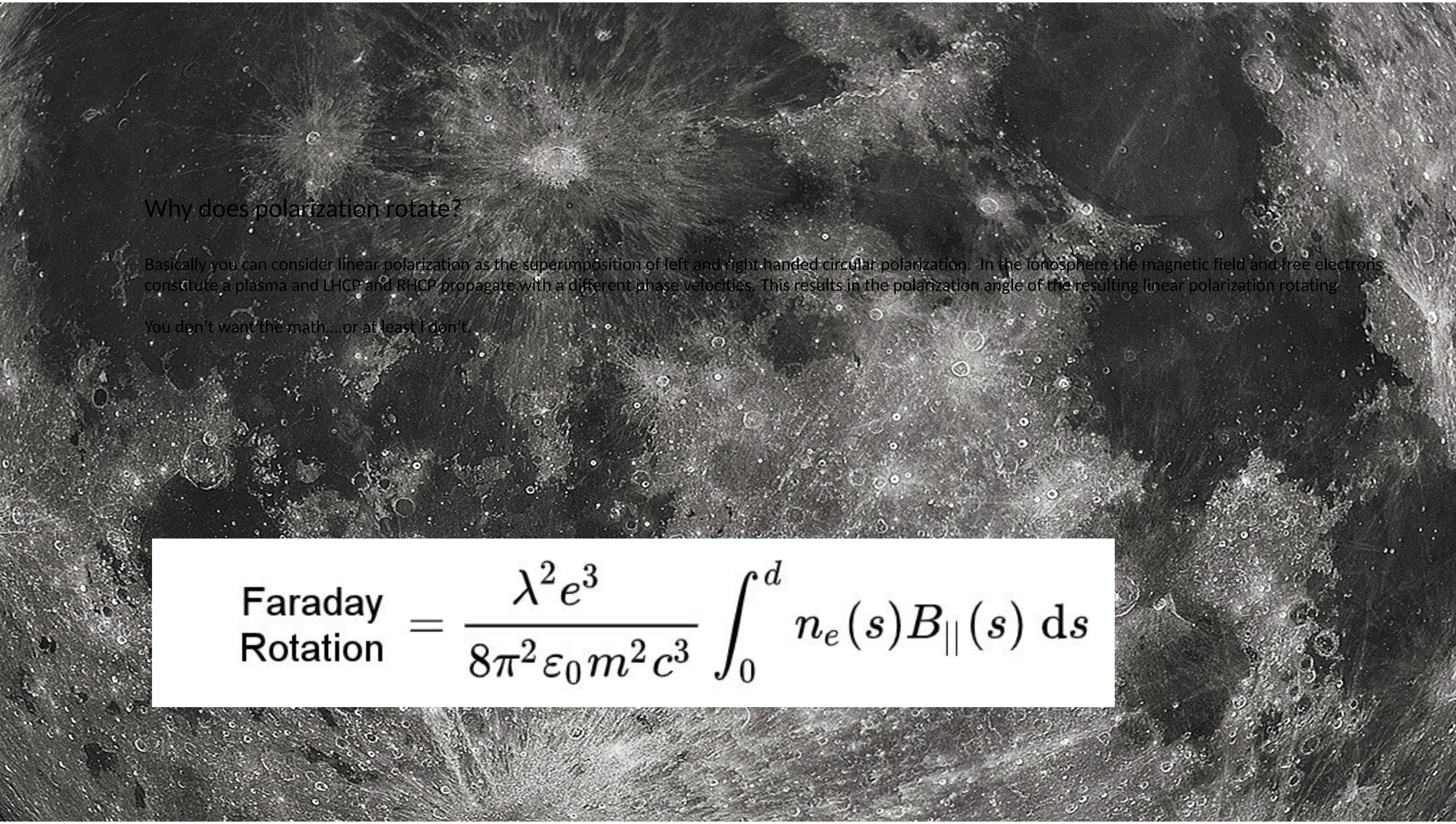


The Faraday Effect

- Free electrons and the earth's magnetic field combine to form a magnetized plasma and induce polarization changes known as Faraday Rotation

This animation shows a 90 degree shift in polarization, from vertical to horizontal. In actual fact it may rotate multiple times depending on the frequency and conditions in the ionosphere





Why does polarization rotate?

Basically you can consider linear polarization as the superimposition of left and right handed circular polarization. In the ionosphere the magnetic field and free electrons constitute a plasma and LHCP and RHCP propagate with a different phase velocities. This results in the polarization angle of the resulting linear polarization rotating

You don't want the math….or at least I don't.

$$\text{Faraday Rotation} = \frac{\lambda^2 e^3}{8\pi^2 \varepsilon_0 m^2 c^3} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

Faraday Rotation

- Below about 23cm, Faraday rotation can be an issue on EME. Linear polarization is rotated. At 70cm the plane of polarization can rotate several times (e.g. 2 rotations or 720 degrees). At lower frequencies polarization can rotate even more.
- Rotation changes with time. It may rotate 180 degrees in a few minutes at 6m, in 20-30 minutes at 2m and in several hours at 70cm. This means you may have to wait longer on 70cm than on 2m for favorable conditions.
- The issue for EME is that a difference between the polarization of the Rx antenna and the polarization of the returning signal give rise to additional loss.
- *As far as EME operation is concerned,* Faraday rotation has no effect on circularly polarized signals

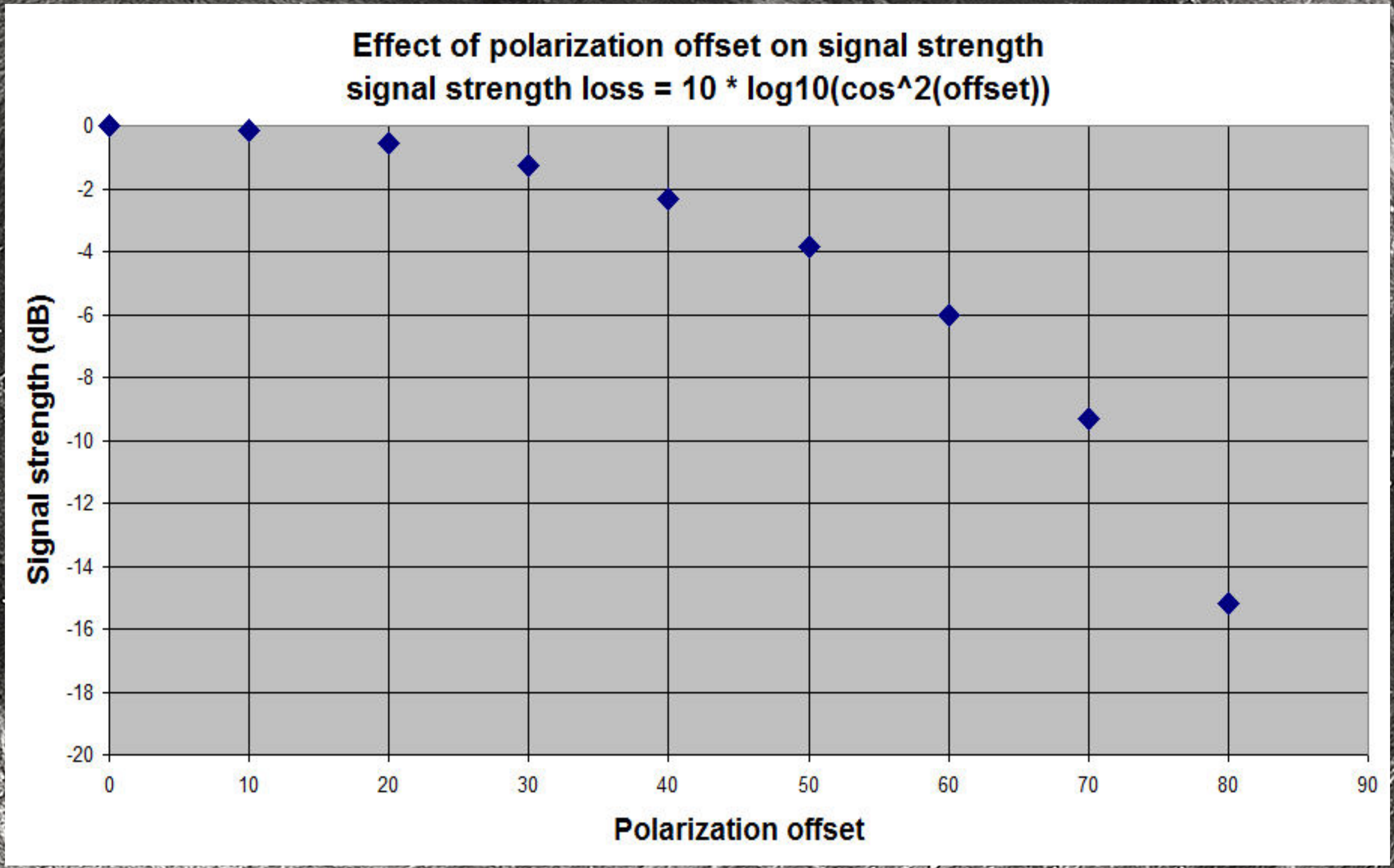
Polarization mismatch losses

A polarization offset of 30 degrees gives about 1.2dB added loss

45 degrees results in 3dB loss

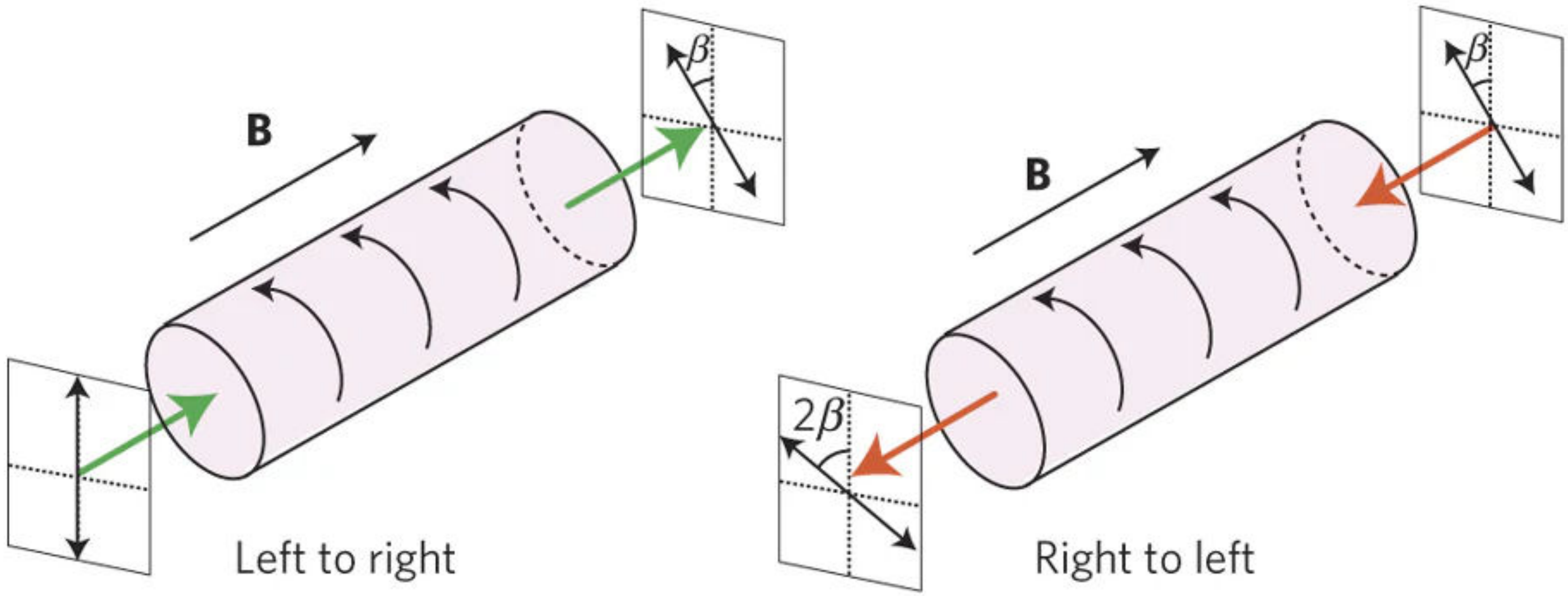
80-90 degrees typically results in 10 to 20dB loss in practice (depends on the band due to polarization scrambling on lunar reflection)

Circular to linear loss is 3dB in theory, but can be slightly lower in practice due to depolarization scattering



Faraday rotation is non-reciprocal

The initial Faraday rotation of a signal on its first pass through the ionosphere is NOT cancelled out by a second pass in the opposite direction as it returns back to earth, even on your own echoes.



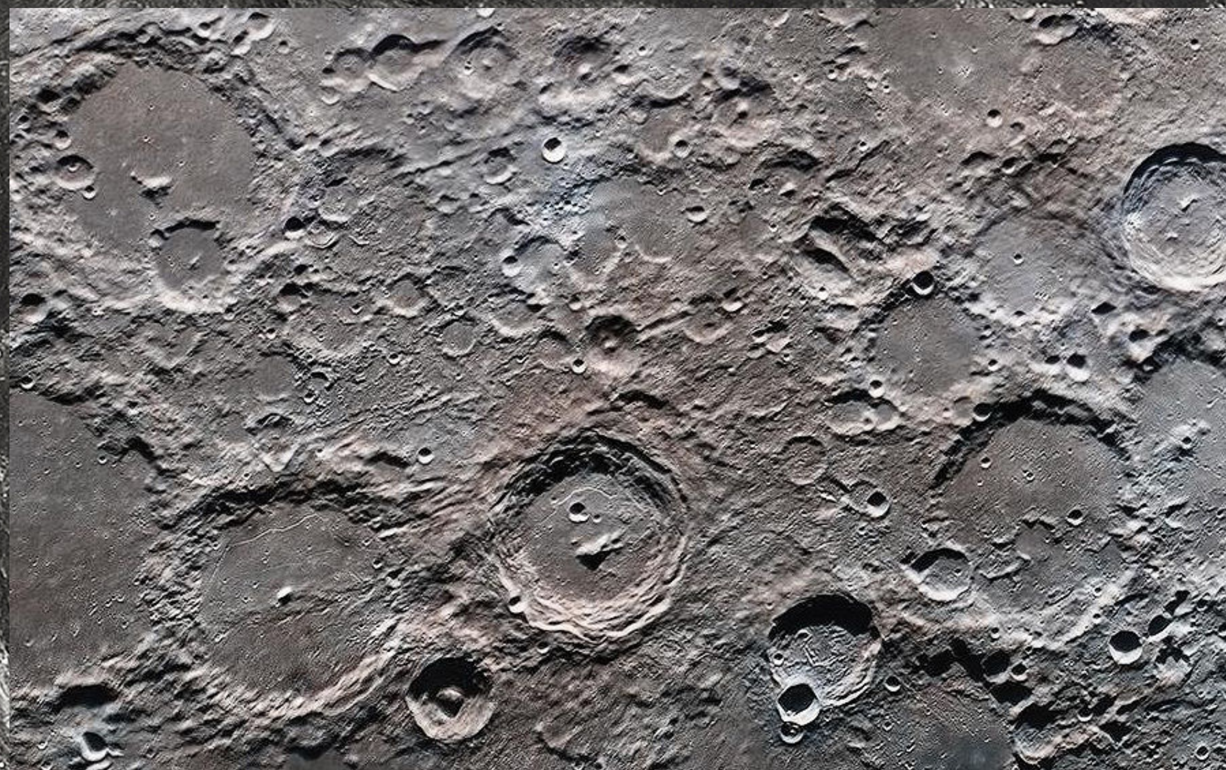
https://www.fiberoptics4sale.com/blogs/wave-optics/99205446-faraday-effect

The signal arrives at the moon

The moon is not a smooth reflector

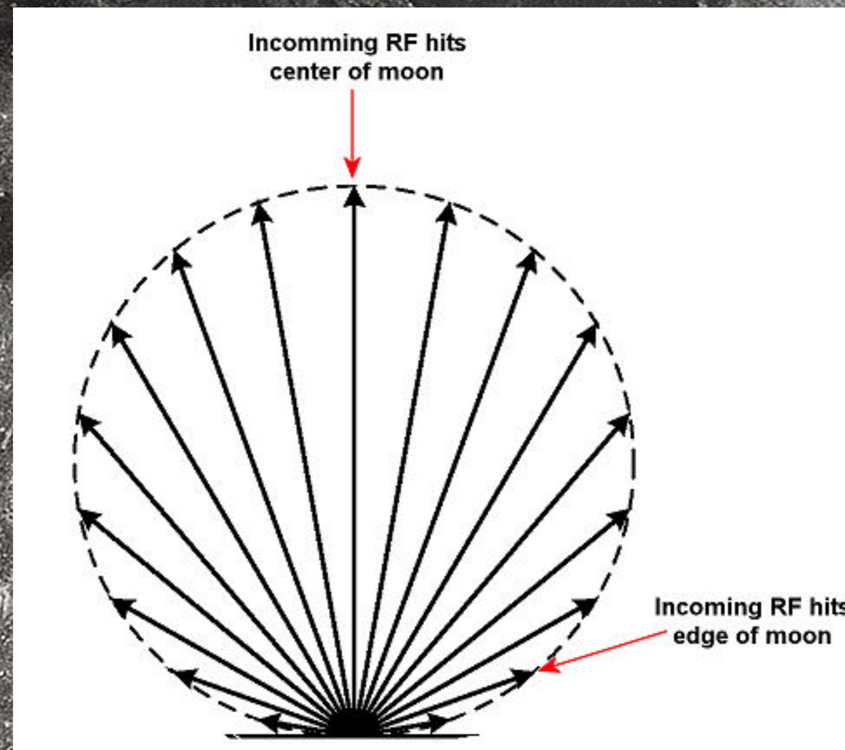
"Nearly the entire Moon is covered by a rubble pile of charcoal-gray, powdery dust, and rocky debris called the lunar regolith"

NASA



Reflection from the Moon

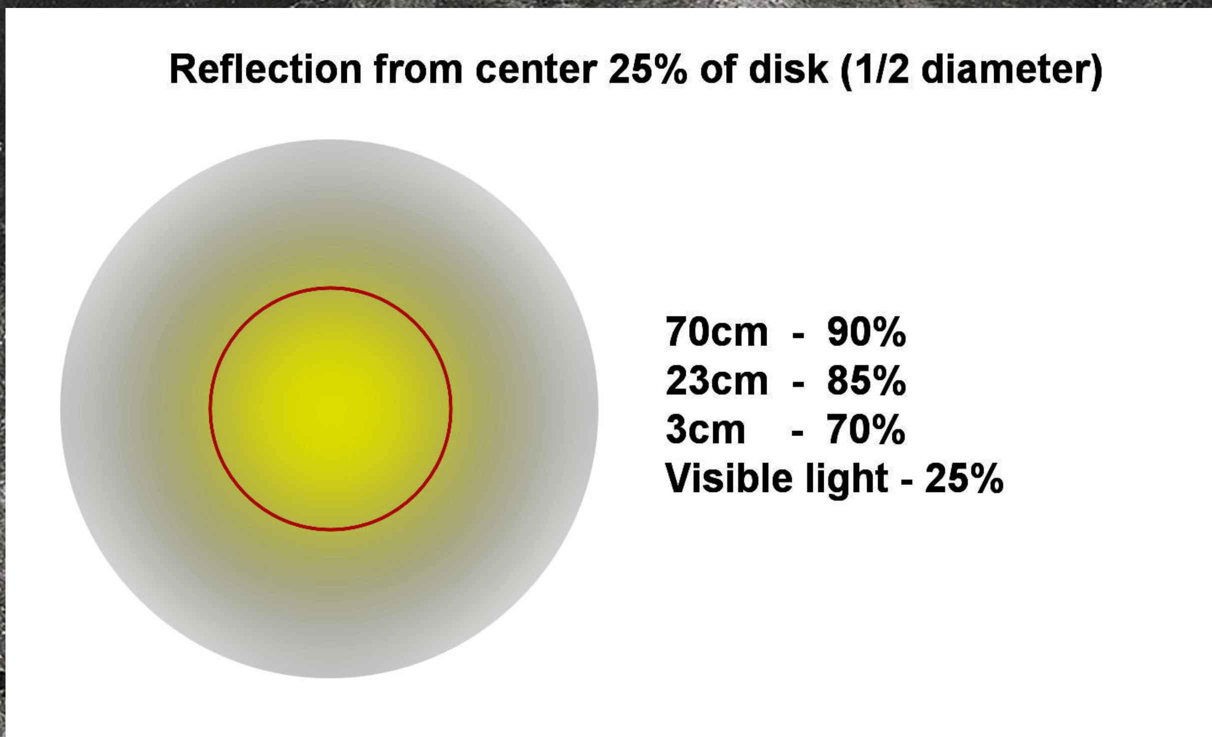
- The surface of the moon is rough. It scatters RF more then reflecting like a mirror. The actual scattering is complex and non uniform, depending on the local nature of the surface.
- The earth is a small (1.8-2 degree) target, so only energy scattered back close to the incident RF direction ever gets reflected back to earth (red arrow)
- The amount of back scattering is lower when the RF strikes the surface at an angle as shown on the right
- Only RF scattered back within about 1 degree of the incident path gets back to earth.



Lambertian scattering model

The earth doesn’t really “rise” unless you are orbiting the moon. From the moon’s surface the earth would appear to slightly wander around a fixed point in the sky

Brightness distribution of the reflection



- Most of the RF reflection actually comes from the central region of the lunar disk
- At the edge of the moon it's "earthrise" and the RF is coming in at a very shallow angle, which is not efficiently reflected back
- At EME frequencies, the moon has a reflection coefficient of about **6.5%**

Phase Change on Reflection

- When an RF signal is reflected back from the moon's surface, there is a 180 degree change of phase
- For linearly polarized signals this is of no consequence as far as EME is concerned. Vertical polarization stays vertical, Horizontal polarization stays horizontal.
- However, for **circular** polarization, Left hand Circular Polarization (LHCP) becomes Right Hand Circular Polarization (RHCP), and vice-versa. The consequence of this for EME is that transmitted signals and received lunar echoes have the opposite sense of circular polarization and the antenna system (usually dish feed) has to deal with this.
- The EME convention is that signals are sent to the moon with RHCP and the echoes are received using LHCP. [*Note that dishes add in a second set of polarization reversal which has to be taken into account*]

Moon Reflectivity

- On average, for purposes of echo strength calculations, the RF reflectivity of the moon is usually taken to be between around 6.5%. As you can see from the plot in the right, there is some scatter and some uncertainty (vertical lines) in the data

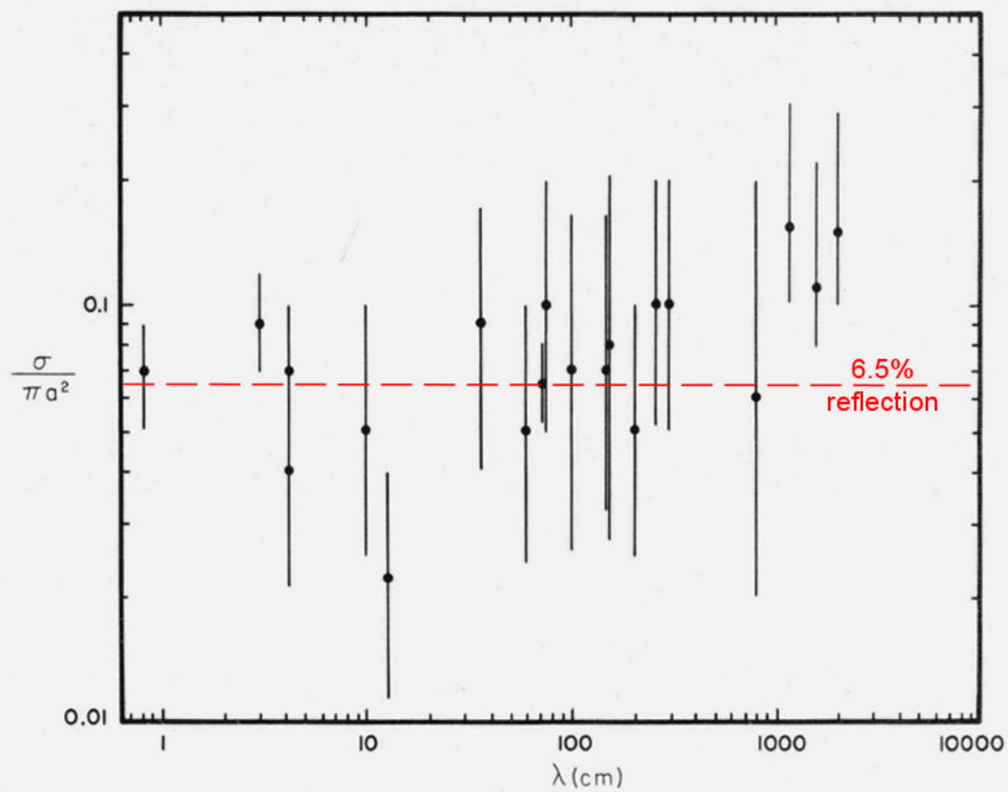


FIGURE 2. *Total effective radar cross section of the moon as a function of wavelength [Evans and Pettengill, 1963a, b; Lynn et al., 1964; Davis and Rohlfs, 1964].*

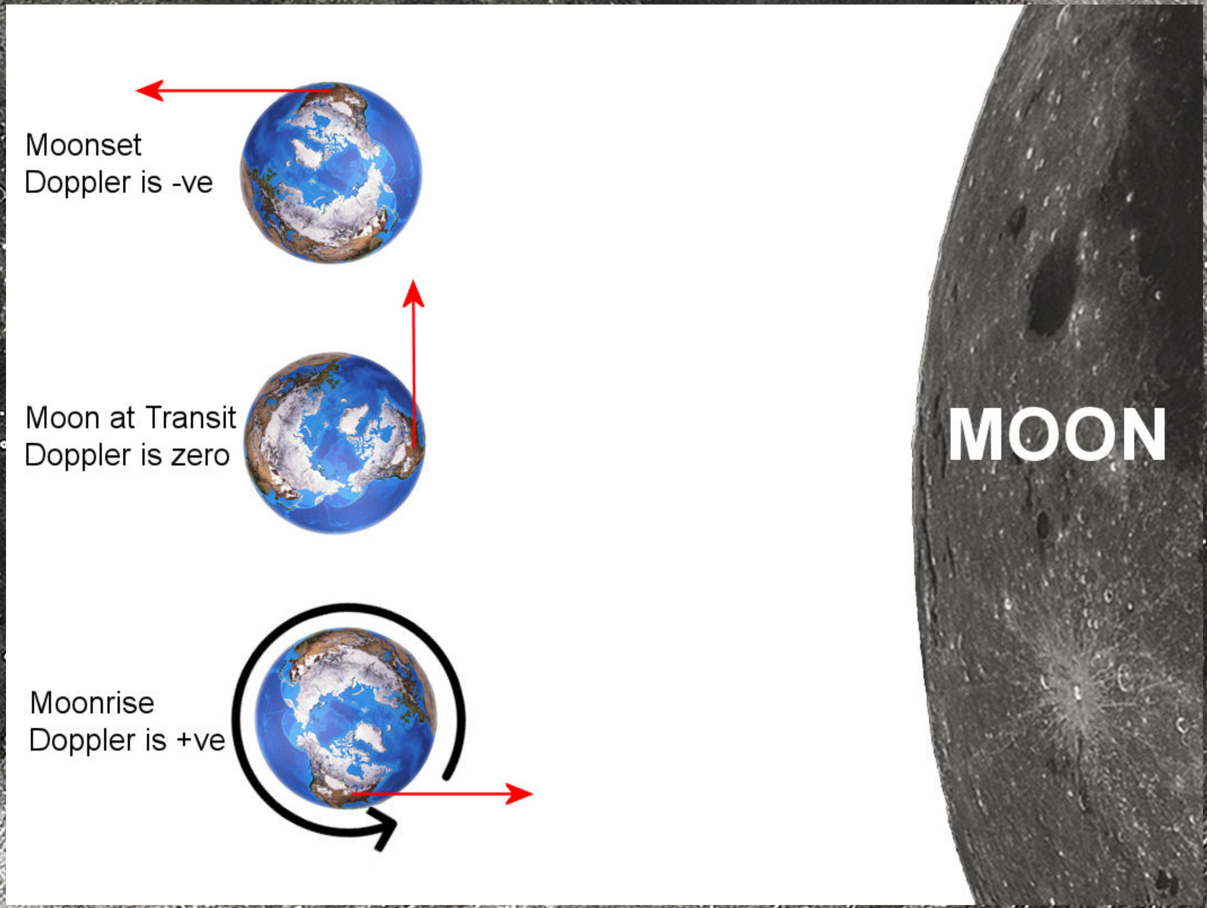
https://nvlpubs.nist.gov/nistpubs/jres/69D/jresv69Dn12p1677_A1b.pdf

Doppler Shift

- Doppler shift is the change in frequency of a signal when distance between the source and the receiver is changing.
- If the distance is increasing, the frequency shift to a lower value (“red shift”)
- If the distance is decreasing, the frequency shifts to a higher value (“blue shift”)

Doppler Shift and the Earth's rotation

- Most of the Doppler shift seen in signals reflected from the moon is the result of the earth's rotation, not the change in the distance from the center of the earth to the center of the moon because that change is quite slow.
- At the surface of the earth (on the equator) the rotation speed is about 1000 MPH. This is what causes the large Doppler shift in EME reflected signals



Magnitude of Doppler shift

- The limits of Doppler shift are related to where you are located. Doppler shift is greater if you are on the equator than if you are closer to the poles
- Doppler shift is linearly proportional to frequency

- At **2m** Doppler shift for NA-EU is between +/- **330Hz**
- At **70cm** Doppler shift for NA-EU is between +/- **1KHz**
- At **23cm** Doppler shift for NA-EU is between +/- **3KHz**
- At **10GHz** Doppler shift for NA-EU is between +/- **24kHz**

Lunar Libration

The moon changes more than its phase over time. *As seen from earth* it appears to "wobble" (librate) due to both optical and physical effects. It's a pretty complicated combination of phenomena, but it can be calculated and predicted

Libration Spreading

- The moon appears to "rock" due to earth's rotation moving the observer from side to side

- Doppler from each side of the moon slightly different results in Doppler spreading of echo

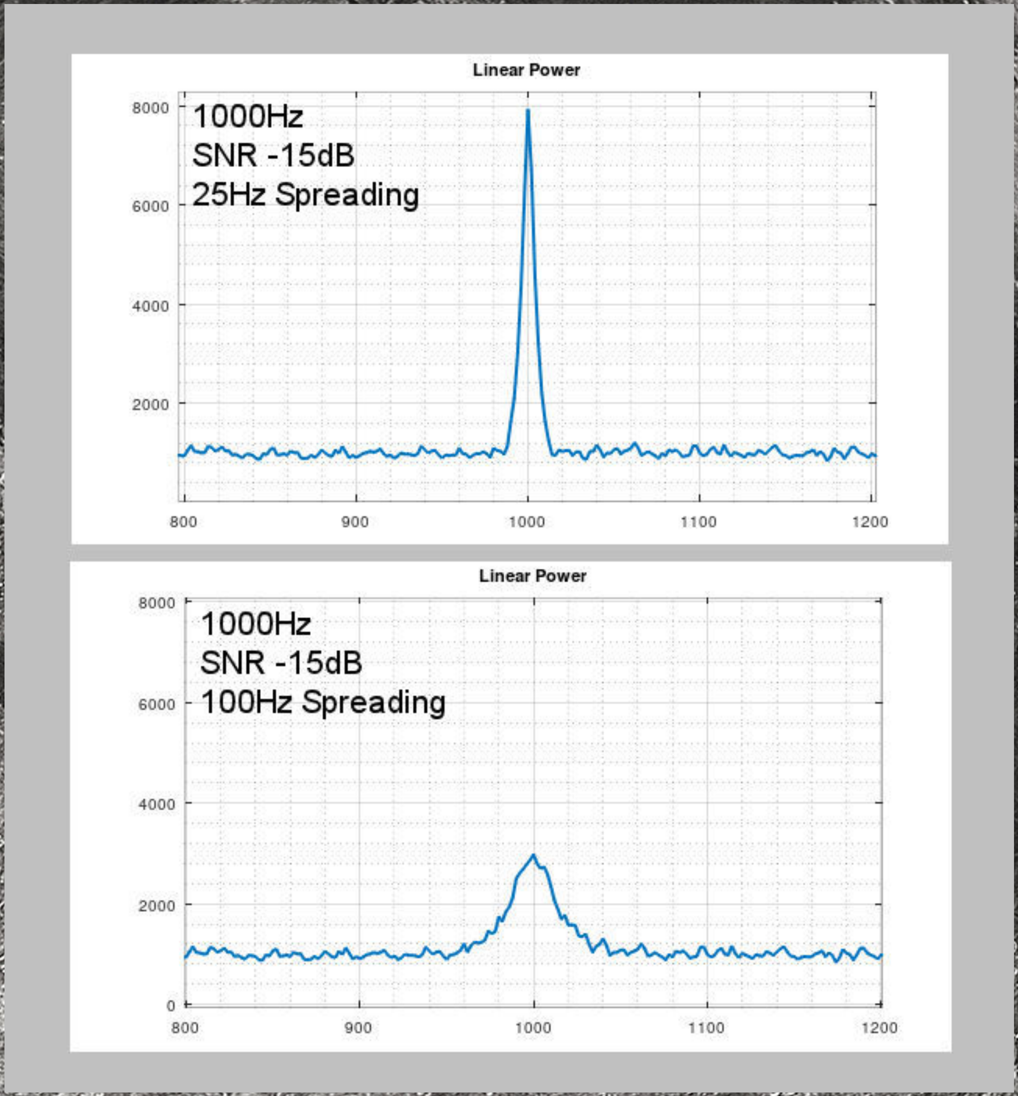
One component of Libration is optical libration, seen below over single moon pass

Libration Spreading

The libration of the moon causes spreading of the signal due to small differences in Doppler shifts from different parts of the moon as it "wobbles". Some are +ve and some are –ve, so the signal spreads around the principle Doppler shift which results from the earth's rotation.

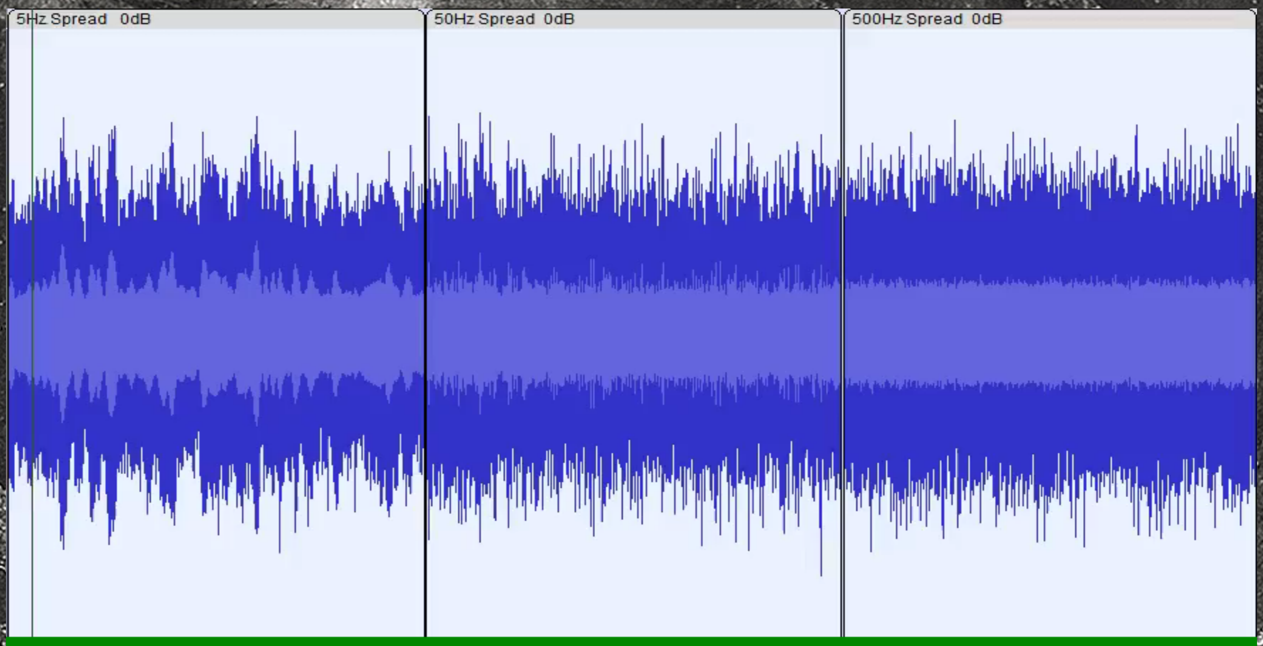
The consequence of spreading is reduced peak height which makes the signal peak smaller and results in it being more difficult to detect and decode.

At 23cm, Doppler shift might be ~ 1500Hz while libration spreading might be ~ 25Hz



The sound of libration spreading

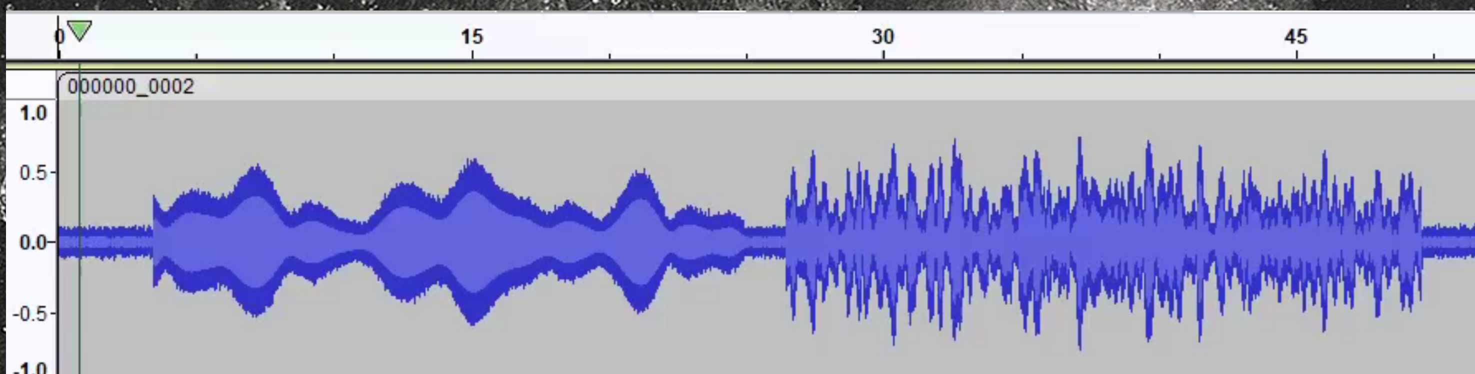
Q65-60 signal at 0dB (*very* strong for EME)



5Hz 50Hz 500Hz

Libration Fading

As reflection from different parts of the moon add up in the reflected signal, differences in amplitude and phase cause fading . The rate of fading is higher (faster) at higher frequencies. Perhaps 1Hz at 2m, a few Hz at 70cm and up to maybe 10Hz at 23cm. Libration fading is a type of multi-path fading or Rayleigh fading. It increases as Libration spreading increases.



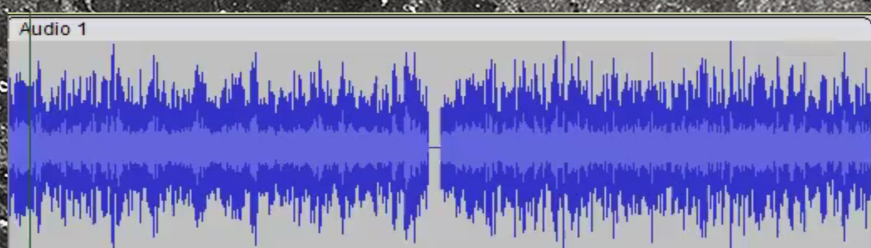
1Hz +20dB carrier 144MHz

10Hz +20dB carrier 1296MHz

Libration Fading

Libration fading is fast QSB and it can make copying weak CW even more difficult at times. For example, if the fading period matches the length of a “dot”, it can chop a “dash” into two “dots”, or it can make a ”dot” disappear entirely.

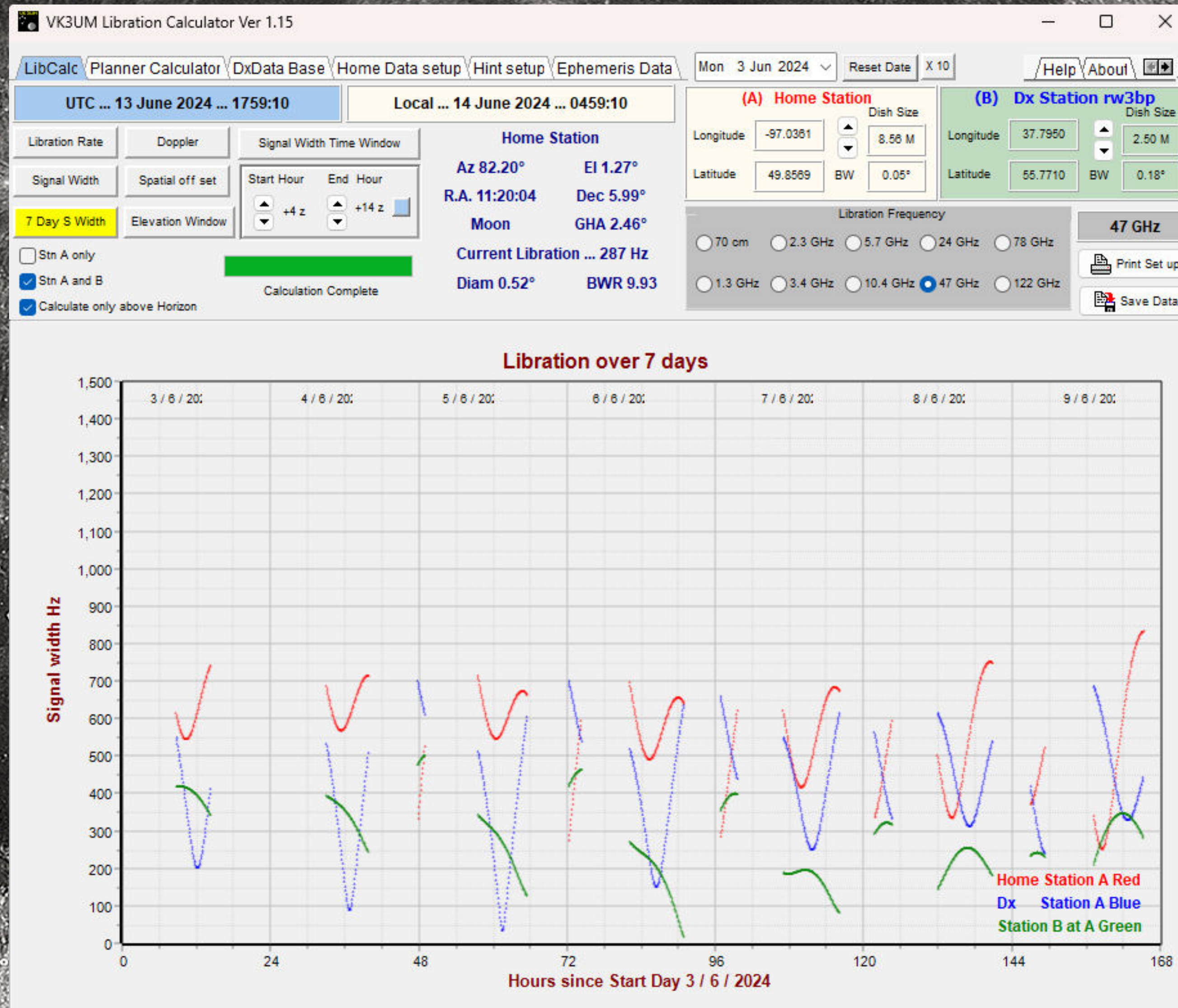
Libration fading effects on CW are most noticeable at 70cm and 23cm. On these bands, higher speed CW (15-20WPM) are made more difficult to copy by libration fading. Most EME CW operation is done at ~ 12-15WPM.



-8dB CW at 20WPM. First at 2m spreading (2Hz) and fading, second at 23cm spreading (25Hz) and fading

Libration spreading can be predicted

- During a QSO stations A and B will see the same libration spreading between them
- However A and B will see different spreading on their own echoes
- Libration spreading between two stations tends to minimize at the start or end of their mutual EME window



Libration spreading and Q65 decoding

- Lower libration = easier decoding of weaker signals
- Choice of appropriate submode (A, B, C, D, E) for given libration further optimizes decoding

Decode probability as a function of SNR, submode and spreading

Q65-60 on 23cm			**Decode Probability**		
Mode	Spreading		-25dB	-26dB	-27dB
60B	33Hz		98%	0%	0%
60C	33Hz		98%	6%	0%
60D	33Hz		98%	10%	0%
60A	5Hz		100%	100%	76%
60B	5Hz		100%	100%	56%
60C	5Hz		100%	76%	18%

Lower spreading -> better decoding
Best decoding requires correct submode

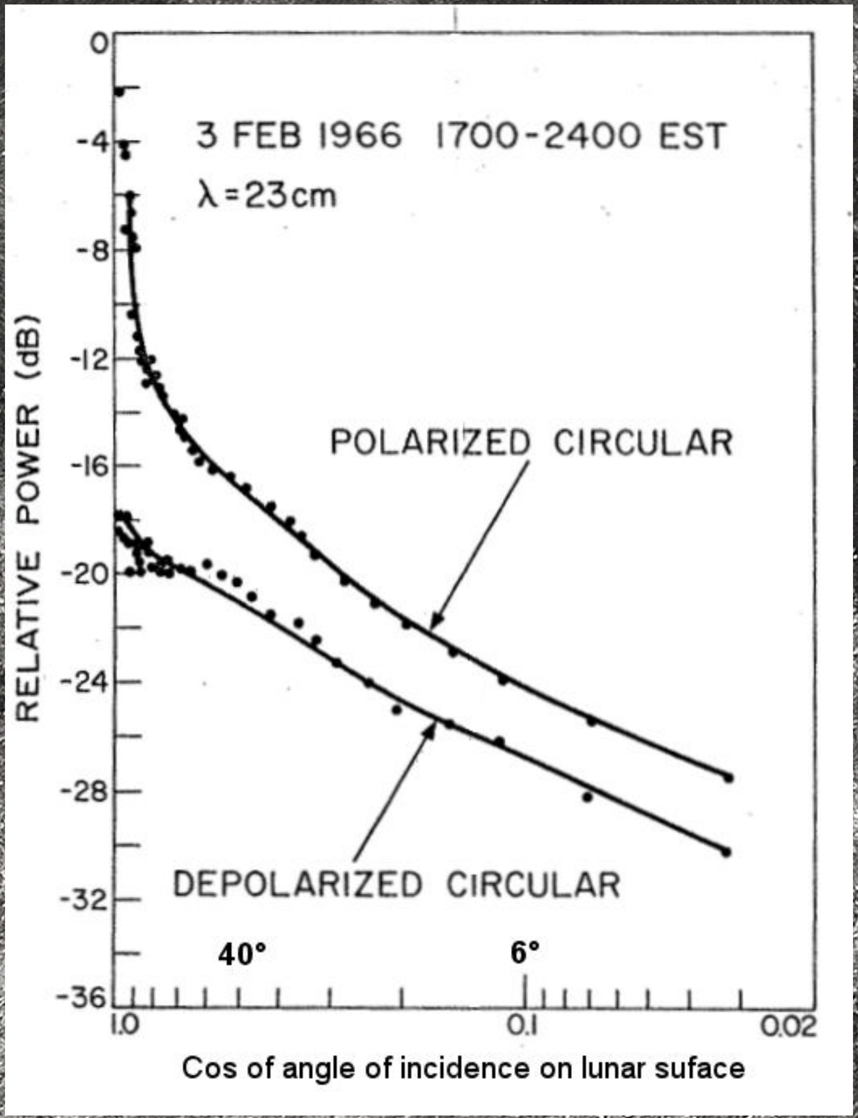
33Hz spreading allows decoding down to -27dB with submodes B, C or D, but D is very slightly better

5Hz spreading allows decodes down to -27dB. Submode A is best. Submode C is not good at -27dB

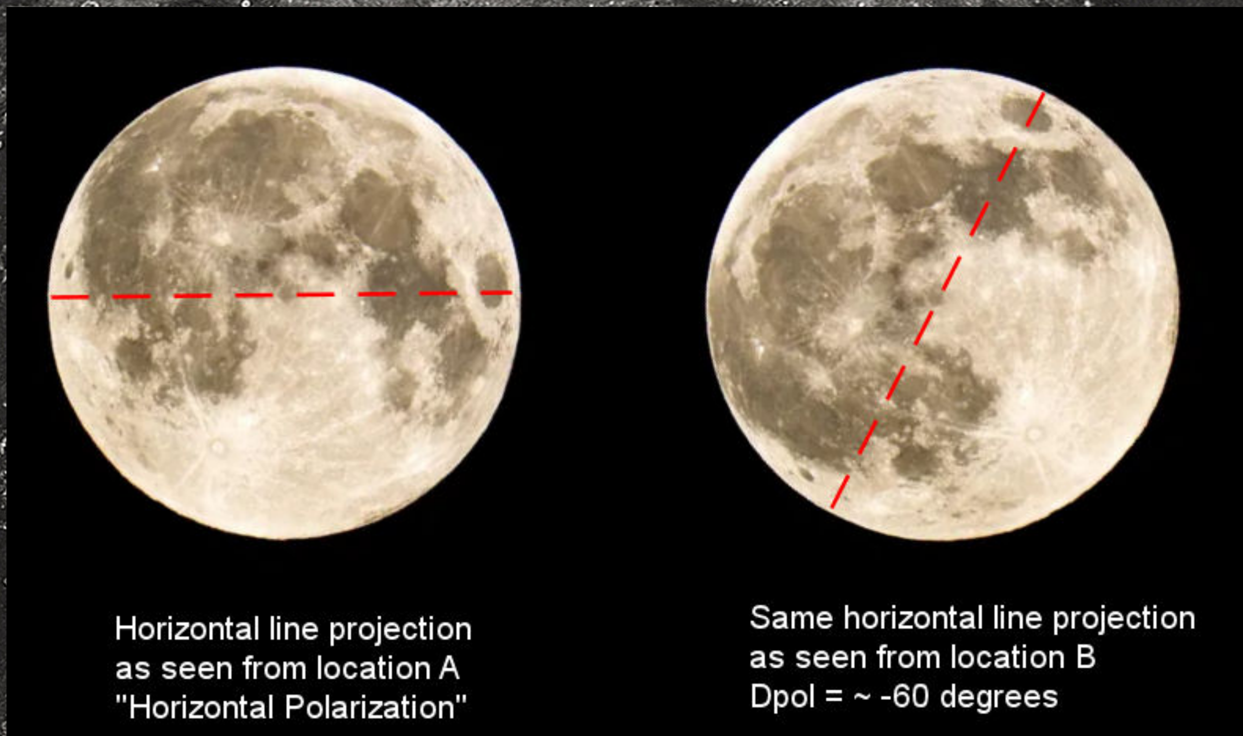
- As you move away from the enter of the disk the angle of incidence increases (as its cosine decreases

- As the angle of incidence increases, there is less power in the reflection and more of the signal power is depolarized

- This is true for both circular and linear polarization



Spatial polarization offset (WSJTX - Dpol)

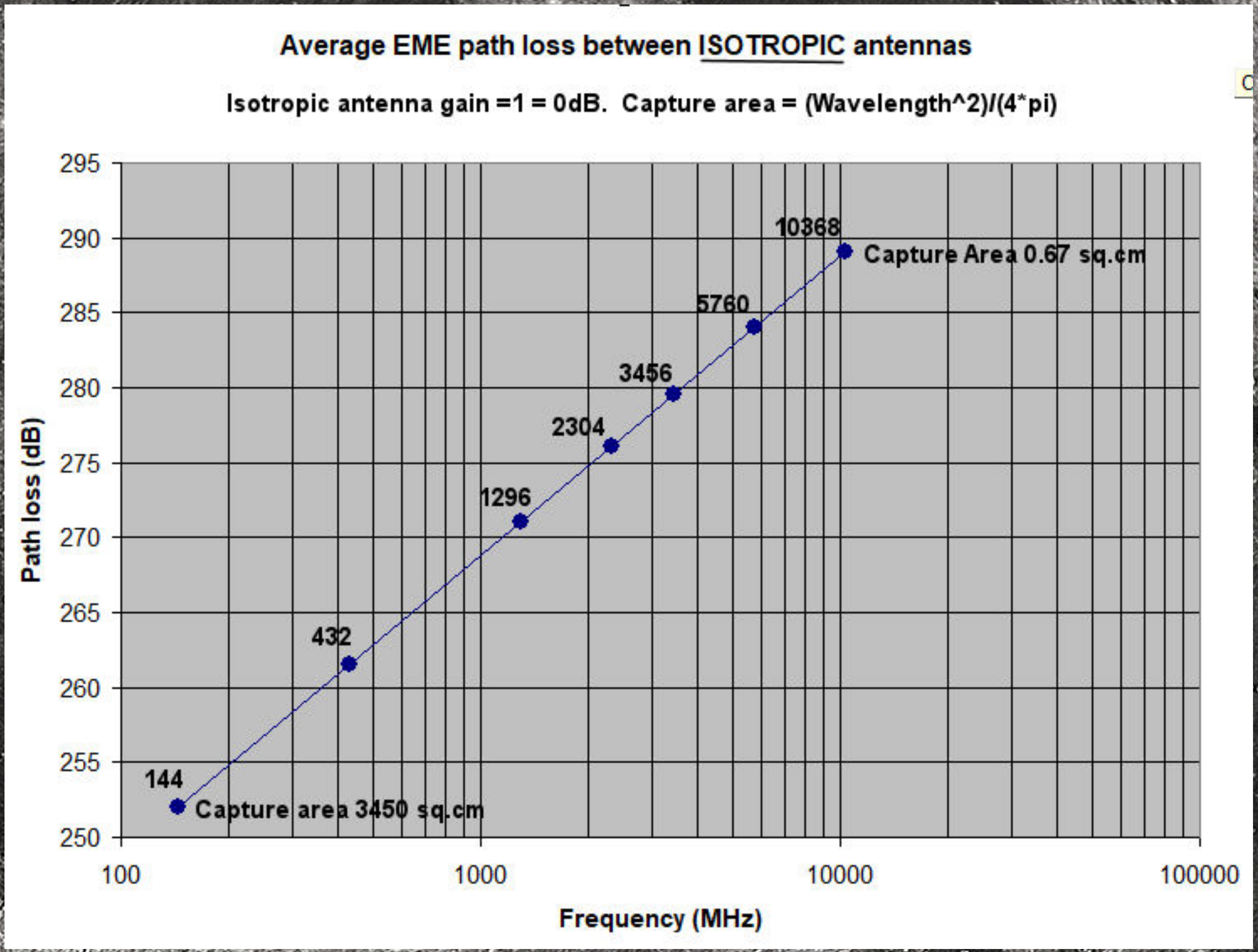


A horizontal line drawn on the moon as seen from Texas would not look horizontal as seen from Germany

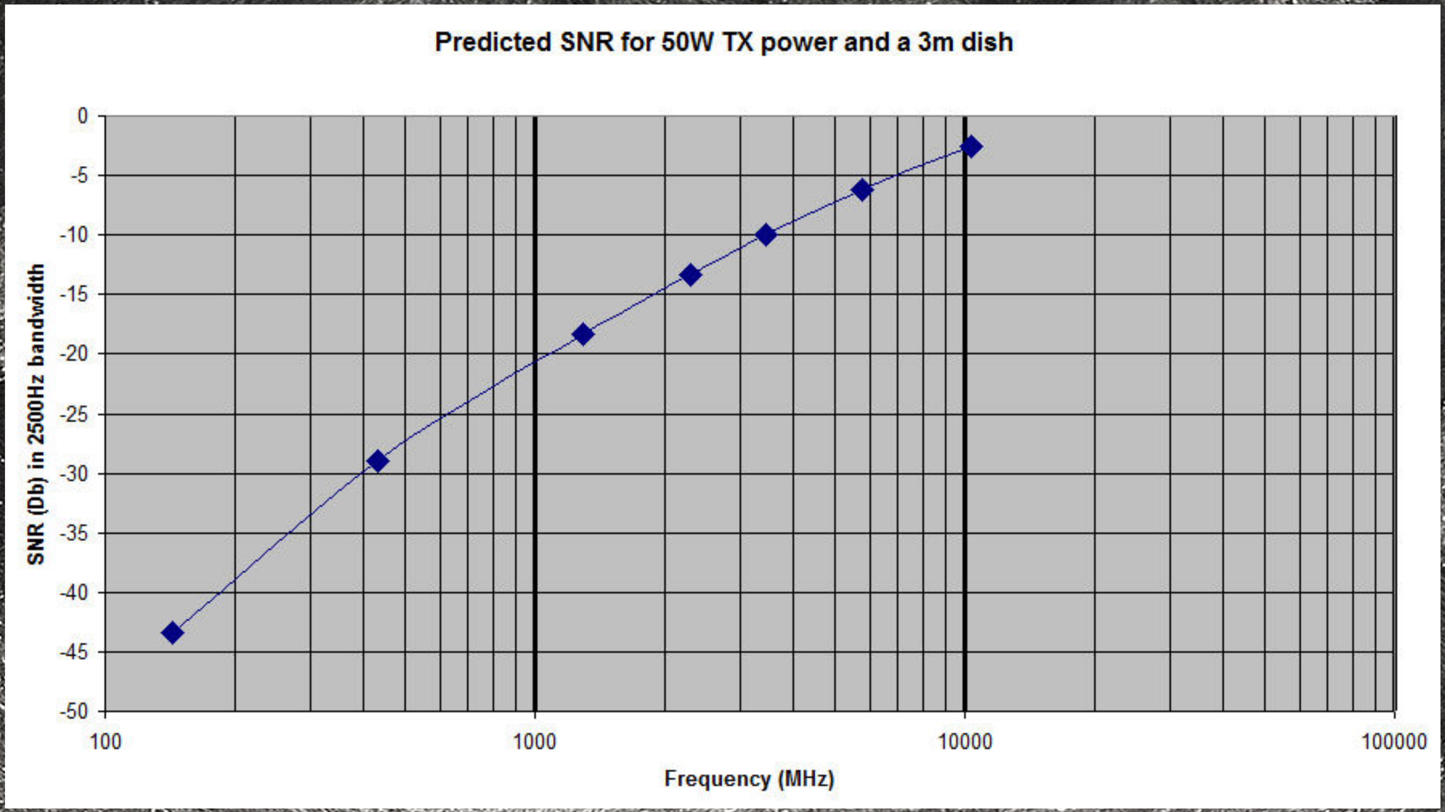
Path Loss

EME path loss is high, but maybe not as high as typical path loss numbers might suggest. They are given for ISOTROPIC antennas (0dBi gain)

Nobody uses ISOTROPIC antennas for EME and on higher bands high gain antennas are physically smaller



For a given power and a given dish size, signals are *stronger* as frequency goes up. The catch is that power at higher frequencies may be harder to obtain and more expensive and the higher the frequency and hence antenna gain, the more accurately the antenna has to be pointed.



Apogee and Perigee

At perigee the moon is closest to the earth, appears larger and the EME path loss (on all bands) is about 2dB less than at apogee

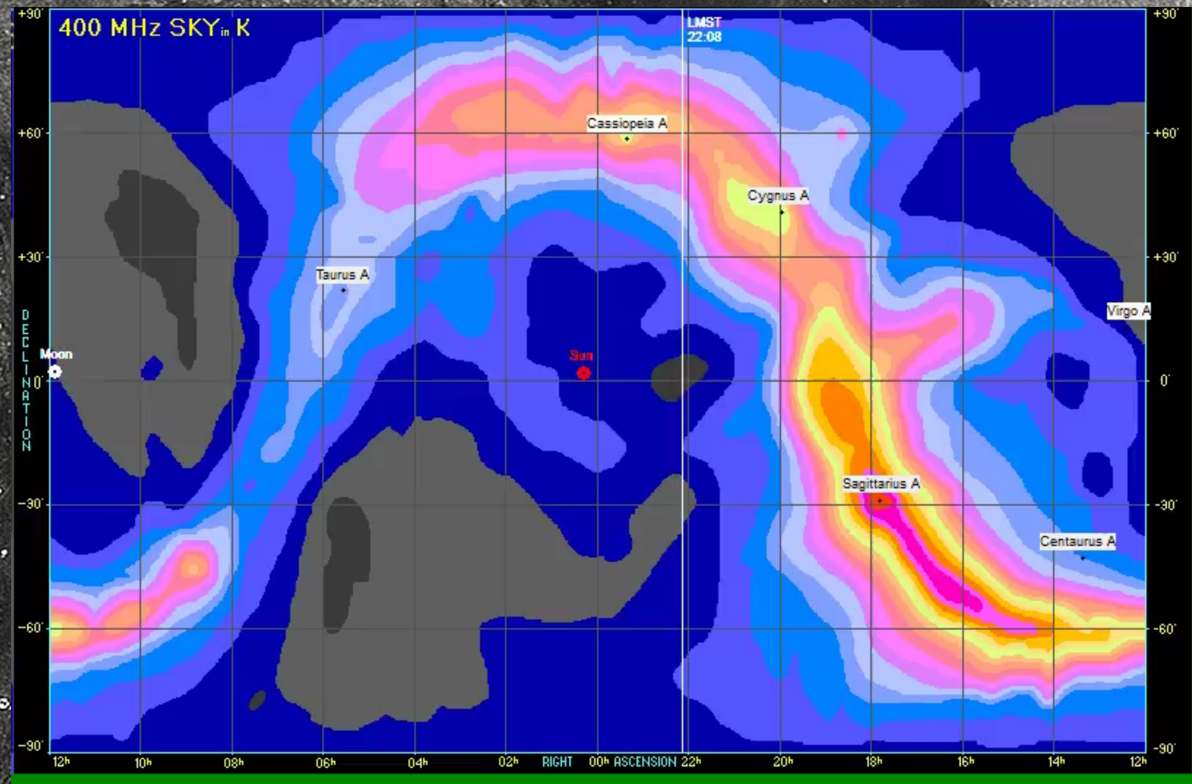
Sky Noise

The sky behind the moon contains noise sources (especially below 23cm). If the moon is in front of a noisy area, signals will be more difficult to decode due to higher background noise

Sagittarius A (the center of the galaxy) is noisy

When the moon is near the sun, sun noise will make signals harder to decode

Sky noise is low in some areas (e.g. Leo) so it will be easier to decode signals when the moon is in that area



The noisy regions (red, yellow, pink) lie in the plane of the galaxy. The quieter regions (dark blue, grey) are in the direction of the galactic poles

Summary 1

Faraday Rotation – at 6m, 2m and 70cm, linearly polarized signals return with unpredictable polarization

- Adaptive polarization. Electrical or mechanical rotation of polarization on Rx
- MAP65 is widely used on 2m for adaptive polarization Rx
- Use Circular polarization (e.g. on 23cm), unaffected by Faraday
- Operate on higher microwave bands (e.g. 10Ghz) which show no Faraday rotation
- Wait – at some point the echo will align with Rx polarization

Spatial Polarization Rotation (WSJTX - Dpol)

- If no Faraday, mechanically compensate for it (e.g. 10Ghz)
- Use circular polarization
- 432 and below, wait for Faraday rotation to cancel it out

Summary 2

Libration Spreading – makes decoding more difficult

- Chose the best Q65 submode for the current value of spreading
- Use programs which predict the spreading to find the best time for a QSO
- Not a huge issue on lower bands, but can be very important on the microwave bands

Sky Noise – makes decoding more difficult

- At 23cm and up, sky noise is low everywhere so it’s not an issue
- At 432 and down, sky noise can be high, so arrange sked for times when the moon is in front of a low noise region of the sky and well away from the sun

Path Loss – makes decoding more difficult

- Work near perigee for best signal strength (2dB stronger than apogee)